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A detector for detecting electromagnetic radiation

Field of the invention

The invention relates to a detector and a method for detecting electromagnetic radiation, in particular a semiconductor detector for detecting electromagnetic radiation having an extended or less focused point of impact, and more particular a semiconductor detector for detecting light waves modulated with a high frequency, where the incident light has an extended or less focused point of impact and/or is of high power.

Background of the invention

It is commonly known that photons from an incident light wave may generate mobile charge carriers (i.e. electron-hole pairs) in a semiconductor material forming a semiconductor junction. If an electric field is applied over the semiconductor junction this actuates the charges to be transported resulting in a measurable electric current in the circuit, which depends on the number of charges generated by the incident photons.

However, the charges delivered to an external circuit by carrier motion in a photodetector material is not provided instantaneously but rather occupies an extended time. This phenomenon is known as transit-time spread and it is an important limiting factor for the speed of operation of all semiconductor photodetectors.

The transit-time spread increases as the active area of a detector is enlarged, simply because it takes longer time for the charges generated in the periphery of a larger active area to reach the collecting electrodes. The increase in transit-time spread corresponds to an increase in the impulse-response time of the detector. This is an unwanted effect since high impulse-response time limits the ability of a photodetector to detect and distinguish between single pulses of a pulse modulated carrier wave as the pulse frequency increases. This is same for other modulation techniques when the frequency of modulation increases.

An enlargement of the active area of a detector, while maintaining a low impulse-response time, may nevertheless be desired if an incident light beam has an extended or less focused point of impact, since too many photons may otherwise impact outside

the active area of the detector. An enlargement may also be desired to properly and without saturation receive and transport charges generated by an intense flux of photons from a high-power light source in a high pulse frequency environment.

Prior Art

The paper *Theory and Design of a Tapered Line Distributed Photodetector* (Jin-Wei Shi and Chi-Kuang Sun, JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 20, no. 11 November 2002) describes a photodetector structure for simultaneously achieving high saturation power and high speed. The detector described is a tapered line distributed photodetector (TLDP), which is a further development of a detector type known as the velocity-matched distributed photodetector (VMPD). By utilizing a tapered line structure and phase matching between optical waves and microwaves in the TLPD structure, a travelling-wave photodetector is more realizable and ultrahigh bandwidth can be attained due to removal of the extra input dummy load that sacrifices one-half of the total quantum efficiency in an common VMPD. The TLPD shown in this paper receives an incident light wave being essentially parallel (i.e. with no incident angle) with respect to the surface of the tapered transmission line and utilizes several photodetectors distributed along an *optical* transmission line, each detector having a *small* active area where the contribution from each detector is added in phase by a low loss *electrical* transmission line. Further, the TLPD shown in the paper presupposes that the light has an incident angle substantially parallel to the transmission line, which implies that the receiving opening of the transmission line limits the size of the impact point of the incident light.

The patent US 6,418,248 (Hays) shows a method and apparatus for a travelling-wave photodetection, having a structure and a function similar to the VMPD and the TLPD described above, where the apparatus receives an incident light wave being essentially parallel (i.e. with no incident angle) with respect to the surface of the optical waveguide. A plurality of discrete waveguide photodetectors is provided. Each discrete waveguide photodetector has a maximum detectable modulation frequency, and each is serially interconnected with all of the others. Each discrete waveguide photodetector provides a respective discrete waveguide photodetector output current, coherently summarized to provide an RF output current. Transmission lines are provided coupling each discrete waveguide photodetector to the summer. Lengths of the respective transmission lines are adjusted for current waves travelling in the respective transmission lines to arrive at the summer in phase and sum constructively.

In summary, the documents above show a technique wherein the active area of a photodetector has been enlarged by using several distributed small detectors. The phase difference of the signals detected by each individual detector is adjusted to sum up constructively at the output of the detector by an electrical transmission line, or similar electrical phase-adjusting arrangement. Hence, the documents may possibly indicate a way of receiving photons from a high-power light source modulated with a high frequency without risking saturation. However, a possibly arrangement following the solution contemplated in these documents would be unnecessarily complicated. Moreover, the documents is silent about a solution to the problems associated with using one photodetector having one substantially continuous area for receiving an incident light beam with an extended or less focused point of impact.

Summary of the invention

The problems mentioned above are solved by the present invention, which provides a semiconductor detector for detecting waves of electromagnetic radiation that are modulated with a high frequency and that have an extended or less focused point of impact on the detector. In particular the invention provides a semiconductor detector for detecting electromagnetic light waves modulated with a high frequency, where the incident light wave may have an extended or less focused point of impact having a cross-section as large as several millimeters, preferably depending on the shape of the incident wave of electromagnetic radiation and/or is of high power. The expression " electromagnetic light wave" should not be interpreted as restricted to visible light. On the contrary, the electromagnetic radiation to be detected may range from infrared to ultraviolet radiation and possibly even further in some embodiments.

The detector comprises a semiconductor junction produced from a substrate having a substantially flat and extended or outstretched surface in preferred embodiments, and at least a first layer arranged on top of said substrate. Further layers may be needed in specific embodiments. Moreover, at least a first and a second electrode that are electrically biased are arranged adjacent to each other on said first layer. The electrodes are separated by an exposed area of the first layer, arranged to receive electromagnetic waves. The semiconductor junction and the electrodes are arranged so as to transform an incident wave of electromagnetic radiation received by the detector to a travelling wave, where said travelling wave propagates along the first electrode towards the output of said first electrode, essentially parallel to the surface of said substrate.

Further, according to the invention an incident wave of electromagnetic radiation has an angle of incident with respect to the surface of the detector. Therefore, the incident

wave is *not* parallel to the surface of the detector, i.e. the incident wave is *not* parallel to the above mentioned travelling wave that propagates along the first electrode towards the output of said first electrode, essentially parallel to the surface of said substrate.

Moreover, the detector comprises at least a first tapered structure arranged on the substrate. The tapered structure is arranged to slow down the signals received from a incident wave of electromagnetic radiation at a given cross section of the first electrode, compared to the signals received at any preceding cross section of the first electrode that is more distant from the output end of said first electrode. This reduces or eliminates the phase difference between said received signals, so that the signals are constructively summed up substantially in-phase at the output of said first electrode.

The expression "on" a layer or similar should through out this document be understood as "on or above" that layer. In other words, the expression includes embodiments in which e.g. an additional layer or additional layers may be present *between* the substrate and the first layer and/or between the first layer and the electrodes. The expression also includes embodiments in which e.g. an additional layer or additional layers may be present *on or above* the electrodes. It also includes embodiments in which e.g. additional layer or layers may be present beneath or within the substrate.

<u>Brief description of the drawings</u>

Preferred embodiments of the present invention will now be described in more detail, with reference to the accompanying schematic drawings, in which:

Fig. 1 shows a top-view to the left and a rear side-view to the right of a detector having a tapered first electrode substantially surrounded by an adjacent second electrode according to a first embodiment of the present invention.

Fig. 2 shows a top-view and a rear side-view of a detector having a stepwise tapered first electrode according substantially surrounded by an adjacent second electrode to a second embodiment of the present invention.

Fig. 3 shows a top-view to the left and a rear side-view to the right of a detector having a tapered first electrode and an adjacent tapered second electrode according to a third embodiment of the present invention.

Fig. 4 shows a diagram illustrating the change in effective permittivity and the change in phase velocity depending on the distance L travelled from the narrow end of the tapered first electrode to the output of said electrode.

Fig. 5 shows a diagram illustrating the increase in travel-time depending on the distance L travelled from the narrow end of the tapered first electrode to the output of said electrode.

Fig. 6A shows a top-view to the left and a rear side-view to the right of a detector having a non-tapered first electrode surrounded by a second electrode, where a tapered delay network has been arranged on said electrodes according to a fourth embodiment of the present invention.

Fig. 6B shows a side-view of a detector having a non-tapered first electrode surrounded by a second electrode, where a delay network has been arranged on said electrodes according to a fourth embodiment of the present invention.

Fig. 7A shows a top-view to the left and a rear side-view to the right of a detector having a non-tapered first electrode surrounded by a second electrode, where a stepwise tapered delay network has been arranged on said electrodes according to a fifth embodiment of the present invention.

Fig. 7B shows a side-view of a detector having a non-tapered first electrode surrounded by a second electrode, where a stepwise tapered delay network has been arranged on said electrodes according to a fifth embodiment of the present invention.

Fig. 8 shows a top-view to the left and a rear side-view to the right of a detector having a tapered first electrode and an adjacent tapered second electrode, where a stepwise tapered delay network has been arranged on said electrodes according to a sixth embodiment of the present invention.

Fig. 9 shows a top-view to the left and a side-view (including a lens or a mirror) to the right of a balanced detector according to a seventh embodiment, having several tapered first electrodes arranged in a substantially symmetrical pattern along a center electrode, and several substantially rectangular second electrodes arranged between and adjacent to every two first electrodes.

Fig. 10 shows a top-view to the left and a side-view (including a lens or a mirror) to the right of a balanced detector according to a eighth embodiment, having several tapered first electrodes arranged in a substantially symmetrical pattern around a center point, and several substantially rectangular second electrodes arranged between and adjacent to every two first electrodes.

Fig. 11 shows a top-view to the left and a side-view (including a lens or a mirror) to the right of a balanced detector according to a ninth embodiment, wherein a tapered delay network has been arranged on the detector according to the eighth embodiment shown in fig. 10.

Detailed description of preferred embodiments

A first embodiment of a detector 100 for detecting electromagnetic radiation according to this invention is shown in fig. 1. Said detector 100 comprises a substrate 110, having a substantially flat and extended/outstretched surface, and a layer 120 formed on top of the substrate 110. It is to be noted that the detector 100 may comprise further layers without departing from the invention.

The substrate 110 and the layer 120 shown in fig. 1 can be made of Si. GeAs, SiGe or some other suitable material used for semiconductors. The choice of material depends on the carrier frequency of the modulated electromagnetic wave. In general Si is preferred for optical carrier frequencies having a wavelength in the invisible to near infrared spectrum, whereas GeAs (or Si Ge) is preferred for carrier frequencies having a wavelength in the near infrared spectrum.

The layer 120 can be formed on the substrate 110 in a well-known manner to create a distributed semiconductor P-N junction, which in a preferred embodiment of the invention enables the substrate 110 and the layer 120 to transform photons from an incident electromagnetic light wave 150 into charges, i.e. electron/hole pairs. The thickness of the layer 120 is preferably selected larger than the absorption length for electromagnetic waves 150 received by the material of the layer 120.

It is to be noted that other embodiments of the present invention may require further layers to form a semiconductor junction or semiconductor junctions. The semiconductor junction may e.g. be formed as a P-I-N, a Shcottky, a metal-semiconductor-metal, a hetrojaction or as some other suitable semiconductor junction without departing from the invention. Moreover, without departing from the invention a substrate 110 and a layer 120 and possible additional layers may be adapted to transform an incident electromagnetic wave 150 into charges even if the wave has a carrier frequency *below* the frequencies in the traditional light spectrum.

Further, as shown in fig. 1, a first tapered electrode 130 and an adjacent second electrode 140 have been arranged on the layer 120 to form a coplanar transmission line. The electrodes are arranged as layers of e.g. Cu, Au or some other suitable high conductive metal layer, and they are separated by an active exposed area 160 of the layer 120 arranged for receiving incident electromagnetic waves.

In a preferred embodiment, the first tapered electrode 130 is connected to a positive (negative) potential and the second electrode 140 is connected to a negative (positive) ground potential, thereby electrically biasing the electrodes to create an electrical field between said electrodes in a well-known manner. However, alternatively and without departing from the invention, a suitable electrical field may be created by connecting the electrodes to other potentials.

The length L of said first electrode 130 may stretch from several μm to several millimeters, preferably depending on the shape of the incident electromagnetic wave. Other lengths L may be required in other embodiments.

The width of the active exposed area 160 of the layer 120 could extend from several μm to several hundred μm, preferably depending on the shape of the incident electromagnetic wave. Other widths may be required in other embodiments.

The length L of the first electrode 130 and the width of the active exposed area 160 is selected so that the generated charges (electrons/holes) reach the electrodes 130, 140 before they recombine (neutralize) and so that the microwave signals from the electromagnetic light wave 150 detected at the narrow end of the tapered electrode 130 (i.e. to the far left in fig. 1) arrive at the broad output end of the electrode 130 (i.e. to the far right in fig. 1) with minimum possible attenuation.

The width of the coplanar strip that meets the tapered first electrode 130 may be in the range of 10μm to several hundred μm, selected so that the signals detected at the far left end in fig. 1 arrive to the far right end in fig 1 with minimum possible attenuation. The thickness of the coplanar strip and the electrodes 130, 140 is preferably 0.1 to 10 μm, though other thicknesses may be preferred in certain embodiments.

The coplanar detector 100 now described is arranged for receiving a modulated electromagnetic light wave 150 (preferably modulated at microwave frequencies), which arrives at an incident angle with respect to the surface of the detector 100. The incident angle is preferably about 90° ± 45° with respect to the surface of the detector 100, where it is preferred that the surface of the detector 100 is essentially parallel to the flat elongated surface of the substrate 110.

As an incident electromagnetic light wave 150 impacts upon the detector 100 the wave 150 will be transformed into charges (electron/hole pairs) in the exposed area 160 of the layer 120 and/or the substrate 110 beneath said exposed area 160. The electrical field caused by the electrically biased electrodes 130, 140 will then actuate the charges

to move in the layer 120 and/or said substrate 110 arranged between said electrodes 130, 140, which excites a traveling electromagnetic wave in a manner well known in the art of coplanar transmission lines. The traveling microwave wave propagates from the narrow end of the tapered electrode 130 towards the broad output end of the electrode 130, i.e. from left to right in fig. 1, where the wave mainly travels along the electrodes 130, 140 in the layer 120, the substrate 110 and the air (and possible other layers) above. In other words, the traveling wave propagates essentially along the *surface* of the detector 100.

However, said traveling microwave wave is slowed down as the wave propagates towards the broader output end 132 of the tapered electrode 130 in fig. 1, i.e. the traveling time increases towards the output of the electrode 130, as illustrated by the solid line in fig. 5. Consequently, the phase velocity is reduced as the wave propagates towards the broader output end 132 of the tapered electrode 130 in fig. 1, as illustrated by the solid line in fig. 4. This is due to the fact that the exposed area 160 of the layer 120 becomes less wide as the tapered electrode 130 widens, which in turn means that the traveling wave has more dielectric in the cross section to travel in. In other words, the effective dielectric permittivity increases towards the output end of the electrode 130, as illustrated by the dashed line in fig. 4.

Consequently, the first electrode 130 of the coplanar transmission line forming the detector 100 shown in fig. 1 is tapered so that the *effective refractive index* for microwaves in the transmission line increases towards the output 132 of the detector 100. The effective refractive index of the transmission line is related to the cross section formed by the first electrode 130, the second electrode 140, the substrate 110 and the layer 120.

Said *effective refractive index* is given by:

$$n_{ew} = \sqrt{\varepsilon_{eff}} \qquad (1)$$

where ε_{eff} is the effective dielectric constant of the transmission line.

As illustrated in fig 5, this implies that the traveling time or the *phase velocity of the signals* received from the traveling wave is reduced at any given cross section of the tapered electrode 130, compared to the phase velocity of the signals received at any preceding cross section of said electrode 130, as the wave travels from the narrow first end 131 to the broad output end 132 of the electrode 130. A proper tapering of the electrode 130 will consequently have the effect that all signals from said travelling wave

received by the tapered electrode 130 will arrive at the broad output end 132 of said electrode 130 with no or negligible difference in time, i.e. phase-matched or nearly phased-matched. In particular, the phase-matching is considerably improved compared to the use of a coplanar detector with a well-known rectangular electrode, or some other un-tapered arrangement.

The *phase velocity of signals* received from said traveling microwave at a given cross section of the tapered electrode 130 is given by:

$$V_{ew}(x) = \frac{c_O}{\sqrt{\varepsilon_{eff}(x)}} \quad (2)$$

where c_O is the speed of light in vacuum, and x is the distance traveled along the tapered electrode 130, as illustrated in fig. 1.

In addition to the advantages of phase-matching described above, a tapering of the first electrode 130 may also reduce/eliminate such backward waves that are common in non-tapered traveling wave photodetectors, which implies that the dummy resistors used in many known velocity-matched distributed photodetectors (VMDP) can be excluded according to this invention.

Thus far a first embodiment of a detector 100 according to the present invention has been discussed with reference to fig. 1. However, the invention is not limited to this first embodiment. On the contrary, the invention can be implemented in a vast variety of embodiments.

A second exemplary embodiment of a detector 200 is shown in fig. 2. The second embodiment is similar to the first embodiment, however illustrating that the first electrode 230 can have a stepwise or trapezium tapering instead of a more triangular tapering as shown in fig. 1. Consequently, it is clear that said tapering can assume a wide variety of triangular shapes, including but not limited to triangles having one angle of about 90°. Moreover, the tapering may assume a conical, trapezium or stepwise shape or some other narrowing shape, including shapes having chamfered or rounded parts/sections.

A third exemplary embodiment of a detector 300 is shown in fig. 3. The third embodiment is similar to the first embodiment, however illustrating that the second electrode 340 may also be tapered, much in a similar way as the first electrode 330. In particular, the first and second electrodes 330, 340 may have identical or a nearly identical shapes in a number of embodiments, though this is not a prerequisite of the

invention. Moreover, as can be seen in fig. 3 the first and the second electrodes 330, 340 is separated and almost surrounded by an exposed area 360 of the layer 320, where the active exposed area is found between said electrodes 330, 340. This is in contrast to the first embodiment according to fig 1., in which nearly the opposite condition prevails as the second electrode 140 nearly surrounds the exposed area 360 of the layer 320. Actually, the second electrode 340 in the first embodiment shown in fig. 1 has an elongated *opening* into which the first electrode 330 extends, where the area between the electrodes 330, 340 is occupied with an exposed area 360 of the layer 320. Consequently, it is clear that a second electrode 340 being adjacent to the first electrode 330 can assume a wide variety of shapes and configurations without departing from the invention.

A fourth exemplary embodiment of a detector 400 is shown in fig 6A–6B. The fourth embodiment is similar to the first embodiment shown in fig 1, however illustrating that the incident electromagnetic wave 450 can be gradually slowed down by a tapered delay network 470, as an alternative or as a complement to a tapering of the first electrode 430 used in the first embodiment. The delay network 470 is arranged on the electrodes 430, 440 and this includes embodiments in which an additional layer or additional layers may be present *between* the delay network 470 and the electrodes 430, 440. The delay network 470 is preferably made of glass, plastic or similar substantially transparent or semitransparent material that enables electromagnetic light waves 450 to pass through the network 470 with some delay.

According to the fourth embodiment an incident electromagnetic wave 450 has to travel a certain length Δy_j in the in the delay network 470, before the wave 450 impacts on the first and second electrodes 430, 440, the layer 420 and the substrate 410.

Given that the material of the delay network 470 is chosen so that an incident electromagnetic light wave travels faster in the medium above the network 470 than in the material of the delay network 470, an incident electromagnetic wave 450 will slow down as it enters the network 470, wherein it continues a slow travel through the network 470.

The delay network 470 is arranged to be tapered so that the thickness Δy_j of the network 470 increases in the direction of propagation of the traveling microwave, i.e. from left to right in fig. 6A–6B corresponding to a propagation from left to right in fig 1. In other words, the thickness Δy_j of the network 470 increases towards the output end

432 of the first electrode 430, which may or may not be tapered in this fourth embodiment.

Consequently, an incident electromagnetic light wave 450 will arrive earlier on the electrodes 430, 440 at a cross section of the delay network 470 having a thickness of Δy_i than at any following cross section of the network 470 having a thickness of Δy_{i+1} or more.

Now, as can be concluded from the discussion regarding the first embodiment, if the electrode 430 is *un-tapered* or *insufficiently tapered*, a signal from an incident electromagnetic light wave 450, detected at a first and more distant cross section of the electrode 430, has to travel a longer time Δt in the transmission line before it reaches the output 432 of the electrode 430, compared to a signal detected at a second cross section a distant Δx nearer said output 432.

However, by using the delay network 470 according to the fourth embodiment of this invention the traveling time Δt may be compensated for by a suitable choice of the material and the thickness of the delay network 470. More precisely, given a certain material in the delay network 470, the thickness Δy_i at a first cross section of the delay network 470 is preferably chosen so that the greater thickness Δy_{i+1} at a second cross, section being a distance Δx nearer to the output 432 of the first electrode 430, causes a additional delay Δt of the arrival of the electromagnetic wave corresponding to the time Δt it takes for a detected signal to travel the distance Δx.

Consequently, a first signal from an incident electromagnetic wave 450 detected by the electrode 430 at a more distant first cross section i of the electrode 430 can arrive at a nearer second cross section $i+1$ simultaneously as a second signal is detected by the electrode 430 at said $i+1$ cross section and hence the newly detected signals sum up with previously detected one in phase. The transmission line and the delay network 470 are designed so that this condition is fulfilled at each cross section of the electrode 430, which implies that all signals detected along the electrode 430 can sum up in phase at the output 432 of the electrode 430.

The discussion above will now be summarized by formulas illustrating the relations needed to obtain a delay/phase-matching:

The propagation velocity V_{ew} of detected microwave signals in the transmission line is given by the effective dielectric constant ε_{eff} of the line, depending on its geometry and materials parameters:

$$V_{ew} = \frac{c_o}{\sqrt{\varepsilon_{eff}}} \tag{3}$$

The traveling time of the electromagnetic light wave signals in section i of the coplanar transmission line is:

$$\Delta t_{ewi} = \frac{\Delta x_i}{V_{ewi}} \tag{4}$$

The propagation of optical signals in optical matching network is

$$V_o = \frac{c_o}{n} \tag{5}$$

where n is refraction coefficient of the optical matching network.

The phase matching condition for each step of the matching network is consequently given as:

$$\Delta y_{i+1} = \Delta t_{ewi} V_o = \frac{c_o}{n} \Delta t_{ewi} \tag{6}$$

where Δy_{i+1} is the thickness of the delay network 470 needed to obtain a phase-match between a first signal, received by the electrode 430 at first step i of the tapered delay network 470 having a thickness of Δy_i, and a second signal received by the electrode 430 at a second step $i+1$ of the tapered delay network 470 having a thickness of Δy_{i+1} and being located nearer the output 432 of the electrode 430.

A fifth exemplary embodiment of a detector 500 is shown in fig. 7A–7B. The fifth embodiment is similar to the fourth embodiment shown in fig. 6A–6B, however illustrating that the delay network 570 may have a stepwise or stair-like tapering instead of a more triangular tapering as shown in fig. 6B. The step-wise tapering may be regarded as a good-enough approximation of a triangular tapering shown in fig. 6A–6B. Consequently, it is clear that said tapering could assume a wide variety of triangular, stair-like, stepwise shapes or some other narrowing shape, including shapes having chamfered or rounded parts/sections.

A sixth exemplary embodiment of a detector 600 is shown in fig. 8. The sixth embodiment is a combination of the third embodiment shown in fig. 3 and the fifth embodiment, shown in fig 7A-7B. This combination illustrates that any suitable tapering of the first electrode 630 and a corresponding and suitable shape of the second electrode 640 may be combined with a delay network 670. The combination may be advantageous if a tapering of the first electrode 630 or a delay network 670 taken alone is insufficient for slowing down the signals detected from the incident electromagnetic light wave 650 so that the signals sum up in-phase at the output of the electrode 630.

Figures 9-11 show an exemplary embodiment of a seventh detector 700 and eighth detector 800 respectively. In these two embodiments a mirror or a lens 780, 880 is used to focus an incident electromagnetic wave 750, 850 on to the detector 700, 800 preferably on the active exposed area 760, 860 of the detector 700, 800. The mirrors or lenses 780, 880 focusing the electromagnetic wave 750, 850 may have a spherical, a cylindrical form or other suitable forms matching the spot shape and size of the electrodes 730, 830 and 740, 840 on the semiconductor chip. The use of mirrors or lenses 780, 880 to focus an incident electromagnetic wave 750, 850 on to the detector 700, 800 is especially preferred in communication systems where two units (e.g. receiver/transmitter or transceiver/transceiver or similar) arranged distant to each other communicates by modulated electromagnetic waves, since a beam of an electromagnetic wave will spread out as it travels a distance, which means that the wave is preferably refocused before any detection.

The detectors 700, 800 shown in fig. 9-10 are preferably implemented in a coplanar technique, similar to the detectors previously discussed in connection with the first, second and third embodiments shown in fig. 1-3 respectively. However, in the seventh and eighth embodiments according to fig. 9-10 there are several tapered first electrodes 730, 830 arranged in a substantially symmetrical pattern, said pattern being a symmetrical linear pattern arranged along one center electrode 791, 891 as in fig. 9 and fig. 10 and/or being a symmetrical pattern arranged in a substantially circular pattern around one center point 892 as in fig. 10. Moreover, there are at least one second electrode 740, 840 arranged between and adjacent to every two first electrodes 730, 830 where an exposed area 160 of the layer is arranged between the electrodes 730, 830 and 740, 840 respectively, so as to separate one electrode 730, 830 from another electrode 740, 840. It is clear that an embodiment may assume a vast variety of symmetrical patterns without departing from a balanced detector according to the invention.

The impedance of the (*i-1*)th section of the center electrode 190 in fig. 9 is given as:

$Z_{i+1}=Z_i/3$, where $i=1,2$ ...

The impedance of the coplanar center electrode 190 in fig. 10 is given as:

$Z= Z_i/n$, where n is the number of sector electrodes 130 and $i=1,2$ ...

The detectors 700, 800 shown in fig. 9–10 respectively are balanced for reducing noise signals. The detected useful signals are correlated and summed up in-phase increasing the bandwidth and the output signal of the detector 700, 800. However, possible noise signals are detected by the electrodes 730, 830 arranged on opposite sides of the center electrode 791 and/or center point 892 as in fig. 10, and they are not correlated, therefore they partially cancel each other.

A ninth exemplary embodiment of a detector 900 is shown in fig. 11. The ninth embodiment is similar to the balanced eighth embodiment shown in fig 10. However, in the ninth embodiment a delay network 970 has been arranged on the electrodes 930, 940 in a similar way as discussed in connection with the fourth, fifth and sixth embodiments shown in fig 6–8. The delay network 170 illustrated in fig. 11 is a transparent and stepwise tapered cylindrical network. However, other embodiments may require a delay network 970 having some other shape, depending on the shape of the electrodes. The shape of a delay network 970 may e.g. be quadratic, rectangular, circular, oval, circle sector, triangular etc., including shapes having chamfered or rounded parts/sections.

This combination illustrates that a balanced detector 900 having any suitable shape of the first electrodes 930 (tapered or not) and a corresponding and suitable shape of the second electrodes 940 may be combined with a delay network 970. A combination may be especially advantageous if a tapering of the first electrodes 930 or a delay network 970 taken alone is insufficient for slowing down the signals detected from the incident electromagnetic wave 950 so that the signals sum up in-phase at the output of the electrodes 930.

Although the present invention has been described in the light of exemplary embodiments, it should be understood that the invention is not limited to these embodiments. On the contrary, the invention includes all possible variations, substitutions and changes covered by the scope defined by the appended claims.

Reference signs

100, 200, 300, 400, 500, 600, 700, 800, 900	Detector for detecting electromagnetic radiation
110, 310, 410, 510, 610	Substrate
120, 320, 420, 520, 620	Layer
130, 230, 330, 430, 530, 630, 730. 830, 930	First electrode
131, 231, 331, 431, 531, 631	First end
132, 232, 332, 432, 532, 632	Second end (output)
140, 240, 340, 440, 540, 640, 740, 840, 940	Second electrode
150, 250, 350, 450, 550, 750, 850, 950	Incident wave of electromagnetic radiation
160, 260, 360, 460, 560, 660, 760, 860, 960	Exposed area
470, 570, 670, 970	Delay network
780, 880, 980	Lens / Mirror
791, 891, 991, 992	Center electrode
892, 992	Center point